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Identification of Text and Symbols on a Liquid Crystal Display Part III: The Effect of Ambient Light, Colour and Size

Kingsley Fletcher[a], Stuart Sutherland[a], Karen Nugent[a] and Michelle Grech[b]

[a]**Maritime Operations Division**
[b]**Maritime Platforms Division**
Defence Science and Technology Organisation

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ABSTRACT

This study aimed to identify the minimum font size that supports fast and accurate identification of text and symbols displayed on an LCD under ambient lighting conditions similar to those in naval ships' operations rooms. A series of letters, numbers and combat symbols were displayed on an LCD for either 106 ms or 173 ms. Participants were asked to identify each stimulus and the certainty of their decision. Letters and numbers were presented in white, red, green and cyan, and symbols were either white or colour-coded. The stimulus heights subtended angles of between 8 minutes and 20 minutes. The study identified the minimum height at which accuracy and certainty were not significantly reduced. Two experiments were performed: one on a land-based sample, and one using Canadian Defence Force personnel during a sea trial in an attempt to identify the potential affects of ships motion and fatigue. Colour significantly improved the identification accuracy and certainty of symbols. Red numbers and letters were identified with significantly lower confidence than white, green or cyan. Some performance degradation was observed during the sea trial, and it is suggested that text and symbols ideally have a height of 16 min or greater, but that a height of 12.5 min or greater is acceptable. A height of less than 12.5 min must not be used for text or symbols that need to be rapidly identified.

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Executive Summary

The Royal Australian Navy ANZAC Class Frigates are being upgraded with an enhanced Anti-Ship Missile Defence (ASMD) capability that includes the development of a new Combat Management System (CMS). As long as good display principles are followed and the limits of human cognitive processing are recognised, increasing the information available to the user on each screen can improve situational awareness and decision making. Reducing the font size is one method of increasing data density, however if the font size becomes too small, reading speed and accuracy will deteriorate. Thus one aspect of the design of the new CMS is to identify how small text and symbols can be made without compromising reading speed and accuracy. An empirical study was performed that examined the effect of size on the ability to accurately and confidently identify rapidly presented text and combat symbols on a liquid crystal display (LCD) under lighting conditions similar to those experienced in ANZAC operations (ops) rooms.

Participants were presented with a series of letters, numbers and combat symbols displayed on an LCD for either 106 ms or 173 ms, and asked to identify each stimulus and their level of confidence in the decision. The stimuli ranged in size from 8 minutes (min) of arc to 20 min. Letters and numbers were presented in white, red, green and cyan. Symbols were either white or coloured. White symbols could be identified by their shape, and coloured symbols had redundant colour coding (both shape and colour) to assist identification. Two primary experiments were performed, one land-based using DSTO employees, and one performed using Canadian Armed Forces members during a sea trial in an attempt to identify the possible effects of ship's motion and observer fatigue on text and symbol identification.

The results indicated that coloured symbols were identified with significantly fewer errors and significantly higher certainty than white symbols, thus confirming the benefits of redundant coding. Red letters and numbers were identified with a lower certainty than the other colours, but did not significantly differ in identification accuracy. Thus red is not a preferred colour unless the colour also conveys information.

The results of the land-based experiment suggested that numbers, letters and symbols should have a height of 12.5 min or greater to maintain accuracy and certainty of identification. No differences were found between the short and long display time conditions. The results of the sea-based experiment suggested that numbers, letters and symbols should have a height of 16 min or greater to maintain optimum identification performance. However, this height could possibly be reduced to 12.5 min without affecting reading speed. For an LCD with luminance and contrast settings appropriate for the prevailing ambient light levels, the following recommendations can be made about character size and colour:

- White and coloured numbers, letters and combat symbols must be displayed at a minimum character height of 12.5 min in order to support rapid and accurate identification, and should be displayed at a minimum character height of 16 min to enable optimum identification performance in an at-sea environment.
- The use of red is not recommended unless the colour is being used to convey information. In this case, a blended red is preferred to pure red for text and symbols.

Authors

Kingsley Fletcher
Maritime Operations Division

Kingsley Fletcher joined DSTO in 2006, having previously worked in telecommunications engineering. He received a Bachelor of Health Science (Hons) in Psychology from the University of Adelaide in 2005, a Master of Business Administration from the University of Adelaide in 1993 and a Bachelor of Engineering (Hons) from the University of Adelaide in 1986. He currently works in the Human Factors Discipline of the Maritime Operations Division, focusing on human-machine interactions in the combat operations rooms of surface ships.

Stuart Sutherland
Maritime Operations Division

Stuart holds an honours degree in Electronic Engineering from the University of Sussex and a Graduate Certificate in Human Factors from the University of Queensland. He began his career designing and building computerised electronics for the theatre. Following this he worked on sensor signal processing, tracking and fusion for military optoelectronic sensors and on the assessment of naval platform vulnerability to optical detection. Recent work includes the assessment of networked naval gunfire support, ergonomic assessments of combat system consoles and seating, advice on operations room design for the RAN's ANZAC ships and running the first ANZAC SEA WARRIOR exercise.

Karen Nugent
Maritime Operations Division

Karen Nugent joined the Maritime Operations Division at DSTO in 2006, as a graduate after receiving a Bachelor Information Technology from the University of Queensland in 2004. Prior to this she was an Architect, having received a Bachelor of Architecture (Hons) from the University of Queensland in 1999 and obtaining registration with the Board of Architects of Queensland in 2005. She now works for the Command Control Communications and Intelligence Division, developing software to improve situational awareness in command and control applications.

Dr Michelle Grech

Maritime Platforms Division

Michelle works for the Maritime Platforms Division within the Defence, Science and Technology Organisation (DSTO) in Australia. Her current work involves maritime focused research on human systems integration and human factors. Dr Grech joined DSTO after completing her PhD in human factors from the University of Queensland in 2005, specialising in fatigue, workload and situation awareness in the maritime domain.

Michelle, a chartered engineer, has spent most of her career working within the maritime industry both in Malta, the UK and here in Australia starting off as a project engineer, engineering consultant, marine surveyor and maritime human factors researcher. Michelle has also been involved in a number of European Union (EU) maritime safety projects. She is periodically involved as a maritime human factors expert in the evaluation of maritime research projects for the EU Director General of Transport

Michelle has recently completed writing a book entitled 'Human Factors in the Maritime Domain' which was published in March 2008.

Contents

1. Introduction

The Royal Australian Navy (RAN) ANZAC Class Frigates are being upgraded with an enhanced Anti-Ship Missile Defence (ASMD) capability. The upgrade will include the development of a new Combat Management System (CMS), which will integrate the ships' war fighting capability by displaying information from sensors such as radar and sonar and allowing the control of weapons. Information is generally displayed on computer screens and, as long as good display principles are followed and the limits of human cognitive processing are recognised, the display of additional information on CMS screens can lead to increased situational awareness and better decision making. Thus, there is often a desire to maximise the information available to the user on each screen. Reducing font size is one method of increasing data density, however if the font size is too small, reading speed and accuracy will deteriorate. One aspect of the design of the new CMS is to identify how small text and symbols can be made without compromising reading speed and accuracy.

Identification of characters displayed on a computer screen is affected by both the visual angle subtended by the character and the number of pixels that comprise each character. Text needs to be both large enough to exceed visual acuity limits, and be comprised of enough pixels to enable an undistorted character shape to be formed. MIL-STD-1472F specifies the minimum text and symbol size to be 21 minutes of arc (min) for coloured characters and 16 min for black-and-white characters, but allows text size to be reduced to 10 min in shared large screen displays (DoD, 1999a). It also specifies that each character be comprised of at least 10 pixels vertically. BSR / HFES 100 states that 16 to 18 min is normally adequate for rapid and accurate identification of individual characters, but allows 10 min when speed of recognition is unimportant (HFES, 2005). It also specifies that Latin alpha-numeric characters need to be at least 9 pixels high. The standards appear to be largely based on studies performed in the 1980s and early 1990s (Chung, Mansfield, & Legge, 1998; Giddings, 1972; Legge, Parish, Luebker, & Wurm, 1990; Legge, Pelli, Rubin, & Schleske, 1985; Legge, Rubin, & Luebker, 1987; Strasburger, Harvey, & Rentschler, 1991), which typically used screens with resolutions between 70 dpi and 80 dpi. At these resolutions, characters with a height of 9 or 10 pixels would subtend a visual angle between 17 min and 19 min at a viewing distance of 650 mm. Thus it is possible that the text height limits in the specifications are driven by pixel effects rather than visual acuity effects. Given that current computer displays can reach resolutions of over 100 dpi, it is possible that text and symbol sizes less than 16 min may now be acceptable.

In a recent study that examined the effect of character size on the ability to identify letters displayed on a computer screen, Sheedy, Subbaram, Zimmerman, and Hayes (2005) verified that legibility of both upper and lower-case letters increased with the number of vertical pixels per character up to 9 pixels, then stabilised. The need for characters to have at least 9 vertical pixels is in close agreement with both MIL-STD-1472F and BSF / HFES 100, but the study did not report the character height at which legibility stabilised in minutes of arc. The study also found that isolated letters had higher legibility than letters presented within words, which they attributed as a manifestation of the crowding effect. This is the phenomenon where it is more difficult to identify characters when presented among other characters than when presented in isolation (Flom, Weymouth, & Kahneman, 1963; Stuart & Burian, 1962).

Legibility refers to the minimum text size at which letters can be identified. However, text and symbols generally need to be several times larger than the minimum legible height before maximum reading speed can be achieved. In a CMS display, it is not enough that the text and symbols are legible to the operator; they must be identified quickly, accurately and easily. In one of the most recent studies on speeded character identification, Chung, Mansfield, and Legge (1998) found that reading speed increased with font size until the letters reached a height of 11 min, after which no further increase in reading speed was achieved. This result was based on reading of meaningful sentences. When random words were used the maximum reading speed decreased approximately 2.4 times. However, it was not reported if this also affected the minimum text size where critical reading speed was achieved. Thus fast and accurate identification may be possible with a character size below 16 min when reading meaningful sentences, but the size necessary for random words or characters is less clear. The identification task faced by CMS operators does not involve reading meaningful words in a sentence structure, but rather requires the identification of symbols and short letters and number strings which do not necessarily form meaningful words. It is therefore not clear whether character heights of 11 min will be sufficient for use on CMS displays.

In a reading task, words presented in sentences and paragraphs must be serially scanned and processed linguistically to extract information and meaning. As identified above the task faced by CMS operators is somewhat different from text reading as they must identify symbols and short letter and number strings which are used to build and maintain situational awareness of the tactical environment. This leads to a less constrained pattern of fixations as attention is directed to the various locations on the screen which contain the information necessary to interpret the display. Thus the task is more akin to scene perception than traditional reading, although both are achieved through a series of eye movements. The most important types of eye movements are fixations, where the eye is relatively stable and visual information is obtained, and saccades, where the eye moves at a relatively high velocity to a new fixation target (Rayner, 1998). The way information is arranged on the screen will have an important influence on the ability of an operator to quickly and effectively extract relevant information from the display, but as discussed above, the size of the text and symbols may also limit the speed at which information can be processed at each fixation point and thus may increase identification time or reduce identification accuracy.

The traditional method of establishing the text size necessary to achieve critical reading speed is to measure the reading rate in words per minute for text of various character sizes. However, as argued above, reading lines of text is not the task of a CMS operator, who gathers information from symbols and short text strings located at various positions on the display screen. Thus the ability to rapidly extract information from discrete stimuli was considered a more appropriate test than the reading speed for words arranged in meaningful sentences. The majority of fixations during reading and scene perception last between 100 ms and 300 ms with an average of approximately 200 ms, and in this time information at the fixation location is processed and the location of the next fixation location is planned. In each fixation it appears that the visual information necessary for object analysis can be obtained within the first 100 ms (Rayner, Inhoff, Morrison, Slowirczek, & Bertera, 1981; Rubin & Turano, 1992; van Diepen, DeGraef, & d'Ydewalle, 1995), but it is also thought that information can be acquired throughout the fixation (Blanchard, McConkie, Zola, & Wolverton, 1984). The task used in the

current study was to identify letters, numbers and symbols that were presented at various sizes for a period of 106 ms before being masked. At this exposure duration the size at which identification performance begins to decline will provide an indication of the minimum size necessary for optimal visual information processing. However, as processing may occur throughout the fixation period, text size may not have a practical affect on reading speed until stimuli cannot be effectively processed in the period of a normal fixation. A display time of 173 ms was also tested to check whether a display time approaching that of a typical fixation would change the size at which stimuli could be effectively identified.

Both accuracy and self-reported certainty were recorded as measures of identification performance. If a visual stimulus is too small to be effectively processed within the viewing time, it is clear that identification accuracy may suffer. However, accuracy may not be a particularly sensitive measure of the processing difficulty as a correct identification may be made from an incompletely processed stimulus, particularly for the simple stimuli used in this study. Thus self-reported certainty was also measured. Models of eye movements propose that a fixation continues until the information at the current fixation point has been processed to a decision criterion level (which is assumed to be word identification), after which attention shifts away and a saccade is triggered (Henderson & Ferreira, 1990; Morrison, 1984; Reichle, Pollatsek, Fisher, & Rayner, 1998). Increased difficulty in processing information at the point of fixation will lead to longer fixations, slower reading speeds and slower response times (Kliegl, Nuthmann, & Engpert, 2006; Rayner, 1998). However, in the current study the viewing time is constrained, and it was reasoned that if the stimulus was not completely processed in the available time the certainty of identification would be affected, even if the stimulus was identified correctly. Confidence is thought to have a role in the adaptive regulation of decisions (Vickers, 1979, 1985) and has been shown to be correlated with response time (Baranski & Petrusic, 1998; Vickers, Burt, Smith, & Brown, 1985). Thus it was considered that the level of certainty would indicate the level of processing that was achieved in the constrained viewing time, and that a decrease in certainty could be expected to result in longer fixations which may result in a slowing identification speed.

Similar to other RAN combat ships, ANZAC operations rooms can operate under either bright or darkened lighting conditions. Under bright conditions the level of ambient light is approximately 260 lux, which is similar to normal office lighting levels and produces photopic conditions in which the cones of the retina dominate. Under darkened conditions ambient lighting is around 1.5 lux, which is much lower than normal indoor lighting levels and produces mesopic viewing conditions where both rods and cones are used. Under low light levels, visual acuity and colour discrimination performance is lower than under bright lighting. Previous studies, which looked at the effects of character size on speed and accuracy of performance, have generally been conducted under normal office lighting levels. Hence, text and symbols on CMS displays may need to be larger than previous studies suggest. Given this uncertainty, the current study aims to explore the minimum acceptable size for text and symbols under lighting conditions similar to those present in combat ships operations rooms.

The first study was conducted in dark and bright lighting conditions in a land based environment similar to previous studies, using participants working ‘normal’ (0900 to 1700) office hours. However, visual perception and cognitive performance may be adversely effected in a ‘real’ ship operational environment under the influence of ship motions. At the moment, little guidance is available as to how on-shore results should be adjusted to allow for the effects of an at-sea environment. Hence, a second study was conducted to identify the smallest text and symbol size that is appropriate for use during onboard naval operations.

In total, the current study consists of three experiments.

1. Experiment 1 examines the effect of character size on the identification accuracy and certainty of white and coloured letters, numbers and symbols under darkened and bright ambient lighting conditions in a land-based study.
2. Experiment 2 was conducted during a sea trial conducted off Nova Scotia, Canada, in an attempt to identify the effect of ships motion on identification performance. Experiment 2 followed the same procedure as Experiment 1, but only used white letters under darkened ambient lighting due to constraints on the time available for testing. Experiment 2 also used a smaller screen with a lower resolution than used in Experiment 1 due to space constraints available during the sea trial.
3. In order to explore whether different display screens may have affected identification performance, Experiment 3 re-tested a subset of participants in Experiment 1 using the same experimental design and procedure as Experiment 2.

2. Experiment 1 – On Land

2.1 Introduction

This experiment examined the effect of size on the ability to identify letters, numbers and combat symbology briefly displayed on an LCD. This experiment was conducted in a motionless environment and used participants who worked normal office hours (0900 – 1700).

2.2 Method

2.2.1 Participants

Twenty-four volunteers working at DSTO Edinburgh participated in the study. Twenty of the participants had previously taken part in an earlier study which aimed to identify the character contrast and luminance levels necessary to achieve optimal legibility (Fletcher, Sutherland, & Nugent, 2009). Their ages ranged from 20 to 42, with a mean age of 31.5 years (SD = 7.6 years). There were equal numbers of males and females. All participants were tested for normal colour vision with the 12 plate Ishihara colour vision test and had 6/6 or better binocular visual acuity, corrected if necessary, using far and near point optical charts. Eight participants had previous exposure to combat symbology.

2.2.2 Apparatus

An Apple M9179LL / A 30" 2560 x 1600 pixel 60 Hz LCD monitor was used to display all experimental stimuli. This was driven by an HP desktop PC with a P4, 3.6 GHz processor, 1 Gb of RAM and a NVIDIA GeForce 7800 GTX 256MB dual DVI video card. Custom software was written to control the stimulus presentation using Java RE 6.0 and PXLab 2.1.6. A Tektronix J17 luminance meter with a J1803 luminance sensor and a J1811 illuminance sensor was used to measure the luminance of the LCD monitor and the ambient light levels. A chin rest was used to maintain a constant viewing distance from the screen.

2.2.3 Stimuli

2.2.3.1 Letter Stimuli

The letter stimuli consisted of one of ten letters, rendered in Verdana font, presented in the centre of eight flanking characters. The letters were based on the Bailey-Lovie letters (D, E, F, H, N, P, R, U, V, Z; (Bailey & Lovie, 1976), however previous use of these letters (Fletcher et al., 2009) found that the letters 'Z' and 'E' were identified with a higher accuracy than the other eight and that participants often responded 'Y' when 'V' was displayed. Participants also often mistook 'D' for 'O'. Thus the letters 'Z' and 'E' were replaced by 'Y' and 'O', giving a letter set of D, F, H, N, O, P, R, U, V, Y. Letters were 7, 9, 11, 14 or 17 pixels high, which translated into 8, 10, 13, 16 or 20 minutes of arc at the viewing distance of 750 mm used in the experiment. It was likely that identification accuracy of the smallest letter height would be affected by the number of pixels as well as the visual angle, but as the aim of the current study is to explore the effect of size on identification at realistic viewing distances this potential confound was acceptable. The letters were created without using font smoothing. Letters were either white (equivalent RGB levels), red (G = B =0), green (R = B =0) or cyan (R =0, G = B). Pure blue was not used because it had lower legibility than red or green at equivalent luminance levels and could not be displayed at sufficient luminance to achieve optimal llegibility (Fletcher et al., 2009). MIL-STD-2525B (DoD, 1999b) proposes the use of cyan to depict 'friendly' units, therefore cyan was used in place of blue. The letters had a luminance of either 20 cd / m^2 or 60 cd / m^2. The lower luminance was used in the 1.5 lux ambient light viewing condition and the higher luminance was used in the 260 lux ambient light viewing conditions. These luminance levels have been found to maximise legibility and produce similar legibility levels under the two ambient light levels (Fletcher et al., 2009).

The letters were surrounded by eight crowding characters which were constructed by superimposing O, X and +. The crowding characters were the same height as the letters. An example of a letter stimulus is shown in Figure 1.

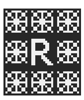


Figure 1: Example of a crowded white letter stimulus

2.2.3.2 Number Stimuli

Number stimuli were prepared in the same manner as letter stimuli, but with the digits 0 - 9 used instead of letters.

2.2.3.3 Symbol Stimuli

Nine symbols were used, which represented either air, surface or sub-surface units that could be hostile, neutral or friendly. The shape of each symbol uniquely identifies its category which is shown in Figure 2. However, colour can also be used to provide additional redundant coding where hostile symbols are coloured red, neutral symbols are coloured green and friendly symbols are coloured cyan. Thus symbols could be either monochrome, where no colour coding is used and white is used for all symbols, or colour-coded, where colour is used to assist classification. The shape of the symbols was derived from MIL-STD-2525B (DoD, 1999b) and created using Milicons software (Guth, 2000).

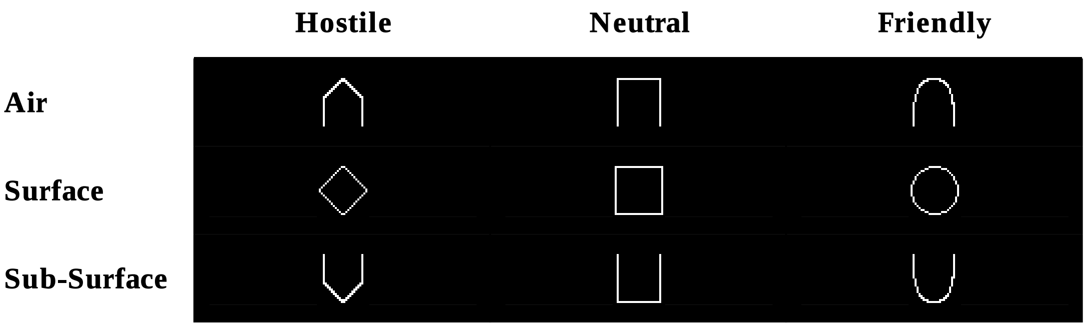


Figure 2: Example of the monochrome combat symbols

The density of symbols on the CMS screen was not expected to be as high as for letters or numbers. While each symbol will have an associated character string of several letters or digits, symbols will not necessarily be clustered together. Thus each symbol stimulus consisted of the symbol presented in the centre of only four flanking characters, not eight, as shown in Figure 3. The symbols had the same heights as the letters and digits, and were created with a luminance of 20 cd / m^2 and 60 cd / m^2.

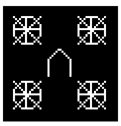


Figure 3: Example of monochrome hostile air stimulus

2.2.3.4 Display Background

All stimuli were displayed on a black background with a luminance of 0.96 cd / m^2 measured in the centre of the screen. Luminance of the background varied from 0.78 cd / m^2 to 1.04 cd / m^2 across the display screen.

2.2.4 Procedure

The stimuli were presented in blocks of letters, numbers and symbols. Each block consisted of a series of trials which presented one stimulus for a short period of time before being masked by a noise pattern in which each pixel was randomly allocated a grey level between 0 and 60. The task was to identify the stimulus and the level of certainty associated with identification. The stimuli varied in size and colour. Each trial was initiated by a mouse-click, whereupon a fixation cross was displayed at the centre of the screen for 200 ms before being replaced with the stimulus, which was displayed for either 106 ms or 172 ms before being replaced by the mask which remained on the screen until the end of the trial Screen buttons which allowed the participant to identify the stimulus and their level of certainty appeared 250 ms after the mask was displayed. Certainty was measured by a six-point scale which consisted of “Completely Certain”, “Highly Certain”, “Moderately Certain”, “Moderately Uncertain”, “Highly Uncertain” and “Complete Guess”. Participants were instructed to select “Complete Guess” if they didn’t see the stimulus because they happened to blink or be looking away when it was presented. The number block consisted of 200 trials (5 sizes x 10 digits x 4 colours, each displayed for 106 ms). The letter block consisted of 250 trials (5 sizes x 10 letters x 4 colours displayed for 106 ms plus 5 sizes x 10 letters x 1 colour (white) displayed for 172 ms). The symbol block consisted of 300 trials (5 sizes x 6 symbols presented 5 times each x 2 colour conditions). Each participant was shown only six of the possible nine symbols to minimise the number of trials. Participants saw either air and surface symbols or surface and subsurface symbols. Participants were randomly allocated to a low or high ambient light condition and the order of block presentation was counterbalanced using a Latin square design. The order of presentation of stimuli within each block was random. Participants undertook symbol identification practice before the experimental session until a 100% identification accuracy was achieved. Participants also undertook a practice letter, number and symbol block at the beginning of the experimental session. The experimental session took approximately 60 minutes, including a 10 minute dark adaptation period.

2.3 Results and Discussion

Data was collected on the accuracy and self-reported certainty for each trial. Trials where a participant reported a certainty rating of “Complete Guess” were removed from analysis to eliminate the effect of guessing on the results. This only occurred for 25 letter trials, 18 number trials and 17 symbol trials, totalling 60 out of the 15,360 trials conducted in the study (i.e., 0.4%). For each participant, the percentage of trials in error and the percentage of trials with ‘completely certain’ responses were calculated in each condition. Accuracy and certainty data were highly skewed, with very few errors made in any size except the smallest and participants responding ‘completely certain’ in most trials with larger stimulus sizes. Thus non-parametric tests using median values were used in the analysis. A significance level of $p = .05$ was used in all tests. The results on the effects of ambient light, colour and stimulus display duration will be presented initially before presenting the main result which was the effect of stimulus size on identification accuracy and certainty.

2.3.1 The Effect of Ambient Light Level

The median and inter quartile range of error and certainty for each stimulus type under the two ambient light and character luminance conditions is shown in Table 1. Mann Whitney U tests were performed to determine whether any reliable differences in errors or certainty existed between the two lighting conditions at any character height. The results of the tests are shown in Table 2. The findings indicate that ambient light appeared to have no significant effect on either of the measures. Thus the data can be collapsed across the lighting conditions in subsequent analysis. The results also suggest that, for any given character height, there should be little difference in speed and accuracy of identification in either darkened or bright operations rooms if a text luminance of 20 cd / m^2 was used with a screen background luminance of 1.0 cd / m^2 in the low light condition, and a text luminance of 60 cd / m^2 was used with a screen background luminance of 1.0 cd / m^2 in the bright light condition. This result is consistent with (Fletcher et al., 2009), where similar legibility was obtained under these two ambient lighting and luminance conditions.

Table 1: Median percentage of error responses and percentage of "completely certain" responses for each stimulus type under low and high ambient lighting conditions. The inter quartile range is in parentheses.

Character Height (min)	Errors Ambient Lighting and Character		Certainty Ambient Lighting and	
	Low	High	Low	High
Letters				
8	0.0% (0.7%)	2.5% (5.7%)	58.8% (51.3%)	55.7% (43.3%)
10	0.0% (0.0%)	0.0% (0.0%)	82.5% (23.7%)	82.5% (21.0%)
12.5	0.0% (0.0%)	0.0% (0.0%)	97.5% (16.9%)	97.5% (15.2%)
16	0.0% (0.0%)	0.0% (0.0%)	97.5% (10.0%)	100.0% (5.0%)
20	0.0% (0.0%)	0.0% (0.0%)	100.0% (5.0%)	100.0% (2.5%)
Numbers				
8	2.5% (2.5%)	0.0% (2.5%)	74.7% (24.2%)	59.5% (42.5%)
10	0.0% (2.5%)	0.0% (0.0%)	96.3% (8.1%)	95.0% (16.9%)
12.5	0.0% (0.0%)	0.0% (0.0%)	100.0% (2.5%)	98.8% (3.1%)
16	0.0% (0.0%)	0.0% (0.0%)	100.0% (3.8%)	100.0% (3.2%)
20	0.0% (0.0%)	0.0% (0.0%)	100.0% (0.0%)	100.0% (0.6%)
Symbols				
8	7.3% (6.3%)	3.1% (4.7%)	75.0% (22.4%)	67.7% (45.2%)
10	2.1% (4.2%)	2.1% (6.8%)	83.3% (13.0%)	74.0% (44.8%)
12.5	0.0% (2.1%)	0.0% (2.1%)	95.8% (7.8%)	89.6% (36.4%)
16	0.0% (2.1%)	0.0% (0.0%)	97.9% (5.2%)	93.8% (28.6%)
20	0.0% (0.0%)	0.0% (0.0%)	100.0% (5.3%)	97.9% (21.4%)

Table 2: Results of Mann-Whitney U tests testing whether any significant differences in errors or certainty existed between the two lighting conditions at each character height

Character Height (min)		df	Errors Z	Errors p	Certainty Z	Certainty p
Letters	8	22	-1.7	.100	-0.3	.773
	10	22	-0.6	.952	-0.3	.750
	12.5	22	-1.0	.317	-0.2	.858
	16	22	-0.6	.952	-1.3	.194
	20	22	0.0	.317	0.0	.973
Numbers	8	22	-1.0	.307	-0.7	.470
	10	22	-1.5	.131	-0.3	.748
	12.5	22	-1.4	.149	-0.8	.399
	16	22	-0.1	.952	-0.2	.842
	20	22	-1.0	.317	-0.2	.807
Symbols	8	22	-1.0	.307	-0.7	.470
	10	22	-1.5	.131	-0.3	.748
	12.5	22	-1.4	.149	-0.8	.399
	16	22	-0.1	.952	-0.2	.842
	20	22	-1.0	.317	-0.2	.807

2.3.2 The Effect of Colour

2.3.2.1 Letters and Numbers

The median and inter quartile range of error and certainty for each colour of letters and numbers at each character height is shown in Table 3. Friedman tests of the probability of equal categories were performed to assess the effect of colour on error and certainty of identification for letters and numbers, and the results are shown in Table 4. There was no significant effect of colour on error at any character height. However, the strong ceiling effect evident in the error results may have reduced the sensitivity of the tests. Colour had a significant effect on identification certainty for letters with heights 8 min, 10 min and 16 min, and for numbers with a height of 8 min. Red was identified with lower certainty than white, green or cyan.

Thus, due to it being identified with lower certainty, red may have been more difficult to identify than the other colours. The effect was not strong enough to translate into an effect on accuracy, however its influence on certainty suggests that red should be avoided for letters or numbers unless the text colour will also be used to convey information. The result that identification accuracy and certainty of cyan letters and numbers did not differ from white or green indicates that the use of cyan may overcome the problems previously identified with the use of pure blue on LCDs (Fletcher et al., 2009).

Table 3: Median error and certainty for stimulus colour for letters and numbers at all character heights. The inter-quartile range is in parentheses.

Character Height (min)		Errors							
		White		Red		Green		Cyan	
Letters	8	0.0%	(2.5%)	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(2.5%)
	10	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)
	12.5	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)
	16	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)
	20	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)
Numbers	8	0.0%	(0.0%)	(0.0%)	(10.0%)	0.0%	(0.0%)	0.0%	(0.0%)
	10	0.0%	(0.0%)	(0.0%)	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)
	12.5	0.0%	(0.0%)	(0.0%)	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)
	16	0.0%	(0.0%)	(0.0%)	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)
	20	0.0%	(0.0%)	(0.0%)	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)

Character Height (min)		Certainty							
		White		Red		Green		Cyan	
Letters	8	60.0%	(72.5%)	40.0%	(52.5%)	60.0%	(52.5%)	55.0%	(65.0%)
	10	90.0%	(30.0%)	70.0%	(32.5%)	90.0%	(22.5%)	90.0%	(42.5%)
	12.5	100.0%	(20.0%)	90.0%	(10.0%)	100.0%	(20.0%)	100.0%	(10.0%)
	16	100.0%	(10.0%)	100.0%	(12.5%)	100.0%	(0.0%)	100.0%	(2.5%)
	20	100.0%	(2.5%)	100.0%	(0.0%)	100.0%	(0.0%)	100.0%	(0.0%)
Numbers	8	75.0%	(50.0%)	50.0%	(50.0%)	80.0%	(42.5%)	70.0%	(41.4%)
	10	90.0%	(20.0%)	100.0%	(20.0%)	95.0%	(10.0%)	100.0%	(15.8%)
	12.5	100.0%	(2.5%)	100.0%	(10.0%)	100.0%	(0.0%)	100.0%	(0.0%)
	16	100.0%	(0.0%)	100.0%	(2.5%)	100.0%	(2.5%)	100.0%	(0.0%)
	20	100.0%	(0.0%)	100.0%	(0.0%)	100.0%	(0.0%)	100.0%	(0.0%)

*Table 4: Results of Friedman tests to assess whether colour had a significant effect on identification error and certainty for letters and numbers. * indicates p < .05, ** indicates p < .01.*

Character Height (min)		df	Errors		Certainty		
			Chi-Square	p	Chi-Square	p	
Letters	8	3	5.5	.141	9.8	.020	*
	10	3	2.0	.572	14.4	.002	**
	12.5	3	3.0	.392	6.1	.106	
	16	3	2.0	.570	8.0	.047	*
	20	3	-	1.000	0.7	.864	
Numbers	8	3	5.6	.132	10.8	.013	*
	10	3	3.8	.290	1.6	.662	
	12.5	3	2.0	.572	2.6	.459	
	16	3	1.4	.706	1.1	.776	
	20	3	3.0	.392	3.0	.392	

2.3.2.2 Symbols

Symbols were presented either in white, where only shape could be used for identification, or colour-coded, where their colour also contributed to identification. The median and inter quartile range of error and certainty for monochrome and colour-coded symbols is shown in Table 5. Wilcoxon sign rank order comparison tests were used to assess the effect of colour coding on identification accuracy and certainty, and the results are shown in Table 6. Identification accuracy was significantly higher for coloured-coded symbols than monochrome symbols for character heights of 8 min and 10 min. Identification certainty was

significantly higher for colour-coded symbols than monochrome symbols for all character heights less than 20 min.

In contrast to the result that colour had no effect on identification accuracy of letters and numbers, the use of colour coding had a reliable and robust effect on the identification accuracy of symbols. Thus it appears that the use of redundant colour coding provided additional information which assisted in the accuracy and certainty at which symbols were identified.

Table 5: Median error and certainty for monochrome and colour-coded symbols at each character height. The inter-quartile range is in parentheses.

Character Height (min)	Errors		Certainty	
	Monochrome	Colour Coded	Monochrome	Colour Coded
8	10.4% (8.3%)	0.0% (1.0%)	54.4% (62.5%)	83.3% (32.3%)
10	4.2% (9.4%)	0.0% (0.0%)	66.7% (37.5%)	95.7% (26.0%)
12.5	0.0% (1.0%)	0.0% (0.0%)	93.8% (20.8%)	95.8% (10.4%)
16	0.0% (0.0%)	0.0% (0.0%)	95.8% (26.0%)	100.0% (4.2%)
20	0.0% (0.0%)	0.0% (0.0%)	100.0% (24.6%)	100.0% (4.2%)

*Table 6: Results of Wilcoxon Sign Rank tests to assess whether colour-coding had a significant effect on symbols. * indicates p < .05, ** indicates p < .01, *** indicates p < .001.*

Character Height (min)	df	Errors			Certainty		
		Z	p		Z	p	
8	1	-4.1	<.001	***	-4.0	<.001	***
10	1	-3.3	0.001	***	-4.0	<.001	***
12.5	1	-1.3	0.206		-2.6	.009	**
16	1	-1.7	0.084		-2.4	.018	*
20	1	-1.7	0.083		-1.9	.058	

2.3.3 The Effect of Display Time

All the previous results relate to a stimulus display time of 106 ms. As an empirical test of whether a display time of 106 ms placed too stringent a limit on visual processing, a 173 ms display time condition was tested for white letters only. This display time was chosen as it approaches the duration of an average fixation. Wilcoxon sign ranks tests were performed to determine if the character height at which errors and certainty became significantly different from the maximum character size differed between the two display time conditions. Plots of median error and certainty at each stimulus height for both display time conditions are shown in Figure 4, and the results of the Wilcoxon signed ranks tests are shown in Table 7. These show that, between the two display time conditions, there was no reliable difference in the character height at which errors or certainty became significantly different from error and certainty at the maximum character height. This suggests that the results of the short display time for the other stimulus types can be considered representative of performance under natural viewing conditions.

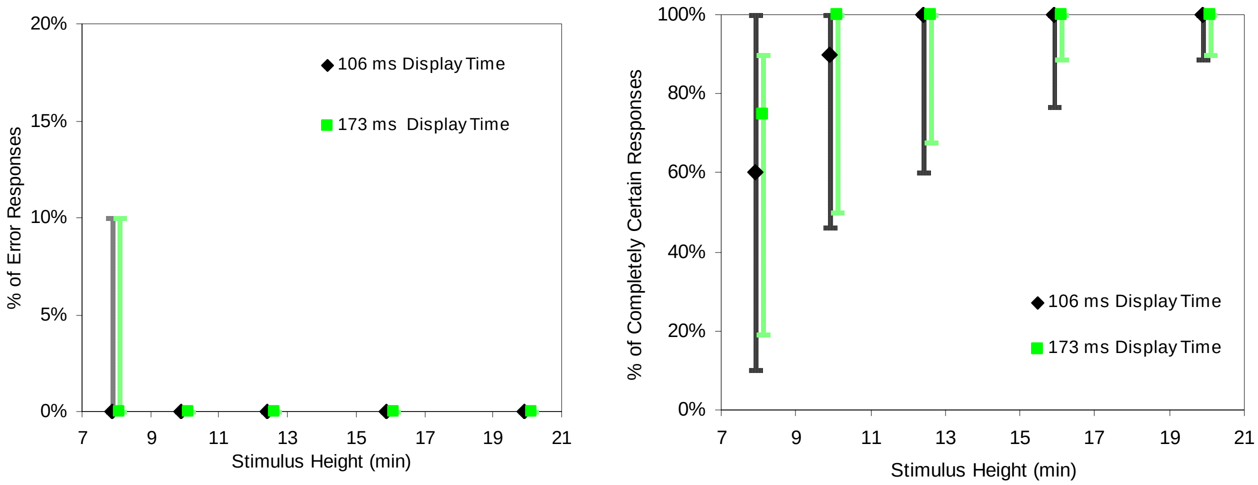


Figure 4: Plots of median identification error and certainty for white letters at each stimulus height for a 106 ms and a 173 ms display time. Error bars represent the 75th percentile range.

*Table 7: Results of Wilcoxon signed ranks tests to determine the character height at which identification error and certainty significantly differed from the maximum character height for white letters at display time of 106 ms and a 173 ms. * indicates p < .05, ** indicates p < .01, *** indicates p < .001.*

	Character Height (min)	df	Display Time 106 ms Z	p		173 ms Z	p	
Errors	8	1	-2.4	.014	*	-2.1	.039	*
	10	1	0.0	1.000		0.0	1.000	
	12.5	1	-1.0	.317		0.0	1.000	
	16	1	0.0	1.000		0.0	1.000	
Certainty	8	1	-3.9	<.001	***	-4.2	<.001	***
	10	1	-3.3	.001	**	-3.0	.003	**
	12.5	1	-1.8	.075		-1.7	.089	
	16	1	-1.9	.061		-1.4	.161	

2.3.4 The Effect of Size

The primary goal of this study was to determine the minimum text and symbol size that could be accurately and confidently identified when viewed for a brief period. The minimum size was calculated as the smallest size where the percentage of responses in error and the percentage of 'completely certain' responses did not significantly differ from the maximum character height of 20 min. Twenty minutes of arc was chosen as the maximum character height as it was the preferred height for black and white characters and close to the minimum height for coloured characters in MIL-STD-1472F (DoD, 1999a). Relative, rather than absolute, measures of accuracy and certainty were used to allow for the possible situation that the identification or certainty may not be perfect at the maximum height. Plots of the median and 75th percentile range of the percentage of responses in error and the percentage of 'completely

certain' for letters, numbers and symbols are shown in Figure 5. Wilcoxon signed ranks tests were used to determine the character heights at which errors and certainty became significantly lower than at a character height of 20 min. Table 8 shows the results of each test for the short display time.

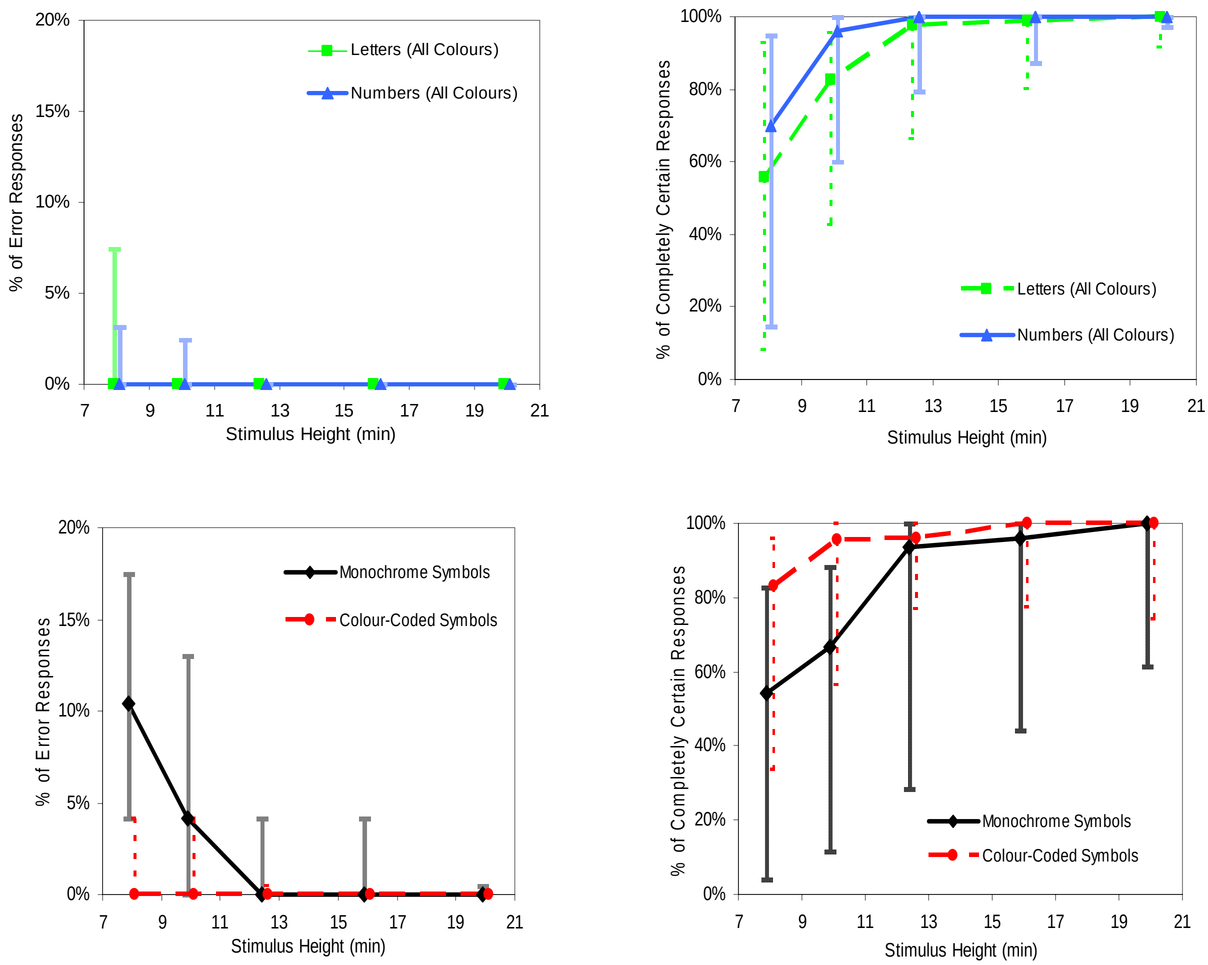


Figure 5: Plots of median error and certainty at each stimulus height for letters and numbers (top row) and monochrome and colour-coded symbols (bottom row). Error bars represent the 75th percentile range.

*Table 8: Results of Wilcoxon sign ranks tests performed at each character height to determine whether errors and certainty were significantly lower than at the maximum character height of 20 min. * indicates p < .05, ** indicates p < .01, *** indicates p < .001.*

Character Height (min)		df	Errors			Certainty		
			Z	p		Z	p	
Letters (All Colours)	8	1	-2.8	.005	**	-3.0	<.001	***
	10	1	-1.3	.180		-4.0	<.001	***
	12.5	1	-1.0	.317		-3.1	.002	**
	16	1	-1.3	.180		-2.3	.023	*
Numbers (All Colours)	8	1	-3.0	.003	**	-4.2	<.001	***
	10	1	-1.7	.096		-3.5	<.001	***
	12.5	1	-0.8	.414		-1.9	.062	
	16	1	-0.8	.414		-1.5	.124	
Monochrome Symbols	8	1	-4.1	<.001	***	-4.3	<.001	***
	10	1	-3.4	.001	**	-4.0	<.001	***
	12.5	1	-1.2	.248		-2.8	.005	**
	16	1	-1.1	.271		-2.1	.033	*
Colour-Coded Sumbols	8	1	-2.4	.014	*	-4.0	<.001	***
	10	1	-2.2	.025	*	-3.1	.002	**
	12.5	1	-1.7	.083		-2.4	.016	*
	16	1	-1.0	.317		-0.7	.465	

From Table 8 it can be seen that, in order to avoid an increase in error rates, letters and numbers needed to have a height of 10 min or greater, and both monochrome and colour-coded symbols needed to have a height or 12.5 min or greater. The sizes necessary to maintain identification certainty were always higher than necessary to maintain identification accuracy. There was a statistically significant decrement in certainty for letters and monochrome white symbols less than 20 min high, for numbers less than 12.5 min height and for colour-coded symbols less than 16 min high.

Thus the two measures lead to somewhat diverging conclusions as to the minimum acceptable stimulus height. Errors in identification are a clear indication that participants had difficulty in processing the stimuli, and the results suggest that letters and numbers should have a minimum height of 10 min, whereas symbols should have a minimum height of 12.5 min. A reduced certainty of identification also suggests that participants had difficulty processing the stimuli, and certainty was affected at larger character heights than accuracy. It is difficult to predict the magnitude of the effect of identification certainty on identification speed, but an inspection of the certainty plot in Figure 5 shows that certainty tends to drop off more rapidly for stimulus heights below 12.5 min than it does at 12.5 min and above. Thus while letters and numbers *must* have a height of 10 min or greater to maintain accuracy performance, it appears that they *should* have a height of 12.5 min or greater to maintain identification certainty. It also appears that symbols must have a height of 12.5 min or greater to maintain both identification accuracy and certainty performance. This size range of 10 - 12.5 min is in close agreement with the results of a related study which estimated that critical reading speed would be achieved at a letter height of approximately 11 min using the same ambient lighting and character luminance conditions (Fletcher et al., 2009). This agreement suggests that the experimental method of the current study is able to provide a valid indication of the character size necessary to achieve maximum reading speed.

3. Experiment 2 – At Sea

3.1 Introduction

The CMS displays need to be used at sea where, particularly during high sea states, the ship's motion may have an affect on human visual and cognitive performance. It is known that ship motion can induce motion sickness and can cause fatigue due to interrupted sleep and increased energy expenditure necessary to maintain balance (Dobie, 2003; Smith, 2001). The aim of Experiment 2 was to examine whether the minimum text and symbol heights found in Experiment 1 need to be adjusted to account for the possible detrimental effects of an at-sea environment. Experiment 2 replicated the procedure of Experiment 1, but used only white letters and low ambient lighting. It was conducted as part of a larger international study investigating the relationship between ships motion, sea-sickness, fatigue and cognitive performance during a 12 day sea trial conducted off the coast of Nova Scotia, Canada.

Experiment 2 was conducted four times during the sea trial, using the following testing schedule:

- Session 1: Pre-deployment, alongside.
- Session 2: 4th day out, open seas. Potentially high sea states.
- Session 3: 8th day out, open seas. Potentially high sea states.
- Session 4: 10th day out, at anchor in sheltered bay. Calm conditions expected.

Session 1 was expected to provide baseline results under calm conditions. The subsequent sessions would be used to identify the possible effect of the at-sea environment. The protocol anticipated that if high seas were encountered during the trial, this may lead to fatigue build up during the voyage. It also identified that sea-sickness may be prevalent during the first half of the voyage, but reduce in the second half due to habituation to ship motions. Thus the results of either Session 2 or Session 3 may be degraded compared to Session 1. The results of each session were analysed to assess whether identification errors or certainty varied across the sessions and to identify the worst case session as representative of performance in an at-sea environment. The results of this session could then be compared with the results of Experiment 1 to establish whether the minimum character height results obtained in the on-land environment of Experiment 1 need to be adjusted to apply to an at-sea environment.

A repeated-measures design was used for Experiment 2 and the absence of a control group meant that it was not possible to separate such variables as fatigue and ship motion effects from the potential learning or practice effects. However, as the task focused on the identification of letters, which is already highly practiced, it was considered that the effects of the repeated administration of the test would not be large.

3.2 Method

3.2.1 Participants

Twelve volunteers, aged between 18 and 44 with an average age of 29.8 years (SD = 8.8 years), were recruited for the trial from the Canadian Armed Forces regular and reserve personnel. Nine were male, three were female.

3.2.2 Apparatus

The experiment was run on a Sony VAIO model PCG-4E3P notebook. It had a 10.6” LCD screen with a resolution of 1280 x 768 pixels.

3.2.3 Stimulus

Only white letters were used in this experiment. The Sony VAIO laptop had a lower resolution than the screen used in Experiment 1, but an equivalent apparent pixel density was achieved by doubling the height and width of the Experiment 1 stimuli and increasing the viewing distance to 1070 mm. Thus the stimuli had an equivalent number of pixels and subtended the same visual angles as in Experiment 1. The stimuli were displayed over a screen background luminance of 1 ± 0.2 cd / m^2.

3.2.4 Procedure

The study was conducted in a forward, port side cabin on board the Canadian Forces Auxiliary Vessel *Quest*. The cabin allowed for controlled ambient lighting conditions of approximately 1.5 lux. Each experimental session consisted of 100 trials (5 sizes x 10 letters 2 display times) and was identical in process to that of Experiment 1. Each participant performed 10 practice trials at the beginning of the session, which presented each of the letters over the range of sizes to be tested. Each experimental session took approximately 15 minutes, including a 10 minute visual adaptation period at the start of each session. At the start of each session, each participant completed the Misery Scale, in which participants are asked to identify their current level of motion sickness on a 11-point scale with anchors of 0 – no symptoms, 1 – stuffy or uneasy feeling in the head, 3 – stomach discomfort, 5 – nauseated, 7 – very nauseated, 9 – retching and 10 – continuous vomiting (Wertheim, De Groene, & Oooms, 1995; Wertheim, Oooms, De Regt, & Wientjes, 1992). Data on ships motion was also collected during each experimental session.

Participants were seated at a viewing distance of 1070 mm from the screen, facing aft. The experimental configuration did not allow for the use of a chin rest, and so ships motion caused some variation in viewing distance. However, an experimenter sat with participants in all sessions and ensured that participants did not appreciably change the viewing distance.

Four experimental sessions were conducted according to the schedule described in section 3.1. Each participant participated in all sessions.

3.3 Results and Discussion

Errors and self-reported certainty were collected for each trial. Trials where ‘Complete Guess’ was recorded were removed from the analysis. This occurred for 84 (1.8%) of the 4,800 trials. For each participant, the percentage of trials with errors and the percentage of trials with ‘completely certain’ responses were calculated for each condition. Accuracy and certainty data were highly skewed, with very few errors made in any size except the smallest, and participants responding ‘completely certain’ in most trials with larger stimulus sizes. Thus non-parametric tests of the median of individual subject percentage errors and certainty were used in the analysis. A threshold significance level of p = .05 was used.

The error and certainty results for each experimental session are shown in Table 9. Plots of the motion data are shown Figure 6. The results of the misery scale are not reported, as participants generally reported zero scores (no problems at all) for all sessions. One participant reported a score of 1 (uneasy, no typical symptoms) for both Session 2 and Session 3, and one participant reported a score of 3 (slight dizziness, warmth, headache, stomach awareness or sweating, but no nausea). Three aspects of the data were analysed: (1) differences between the experimental sessions, (2) the effect of viewing time and (3) the letter heights at which accuracy and certainty were affected under the short viewing time conditions.

Table 9: Median error and certainty for white letters at both 106 ms and 173 ms viewing times for each character height for each session of Experiment 2. The inter-quartile ranges are in parentheses.

		Character Height (min)	Experimental Session: Session 1		Session 2		Session 3		Session 4	
106 ms Display Time	**Error**	8	10.6%	(23.3%)	20.0%	(26.3%)	10.0%	(6.9%)	10.6%	(17.5%)
		10	0.0%	(12.5%)	0.0%	(2.8%)	5.0%	(10.0%)	0.0%	(0.0%)
		12.5	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(10.0%)	0.0%	(10.0%)
		16	0.0%	(0.0%)	0.0%	(10.0%)	0.0%	(0.0%)	0.0%	(0.0%)
		20	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)
	Certainty	8	78.9%	(32.5%)	85.0%	(31.3%)	100.0%	(52.5%)	86.7%	(33.6%)
		10	100.0%	(12.5%)	100.0%	(13.9%)	100.0%	(32.5%)	100.0%	(20.0%)
		12.5	100.0%	(10.0%)	100.0%	(12.5%)	95.0%	(32.5%)	100.0%	(11.1%)
		16	100.0%	(0.0%)	100.0%	(10.0%)	100.0%	(0.0%)	100.0%	(10.0%)
		20	100.0%	(0.0%)	100.0%	(2.5%)	100.0%	(0.0%)	100.0%	(0.0%)
173 ms Display Time	**Error**	8	10.0%	(13.3%)	0.0%	(12.5%)	5.0%	(10.0%)	0.0%	(10.0%)
		10	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(10.0%)	0.0%	(0.0%)
		12.5	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(10.0%)
		16	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)
		20	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)
	Certainty	8	85.0%	(20.0%)	95.0%	(52.5%)	95.0%	(35.0%)	100.0%	(29.2%)
		10	100.0%	(12.5%)	100.0%	(12.5%)	95.0%	(30.0%)	100.0%	(2.5%)
		12.5	100.0%	(10.0%)	100.0%	(10.6%)	100.0%	(10.0%)	100.0%	(10.0%)
		16	100.0%	(0.0%)	100.0%	(0.0%)	100.0%	(0.0%)	100.0%	(0.0%)
		20	100.0%	(0.0%)	100.0%	(0.0%)	100.0%	(0.0%)	100.0%	(0.0%)

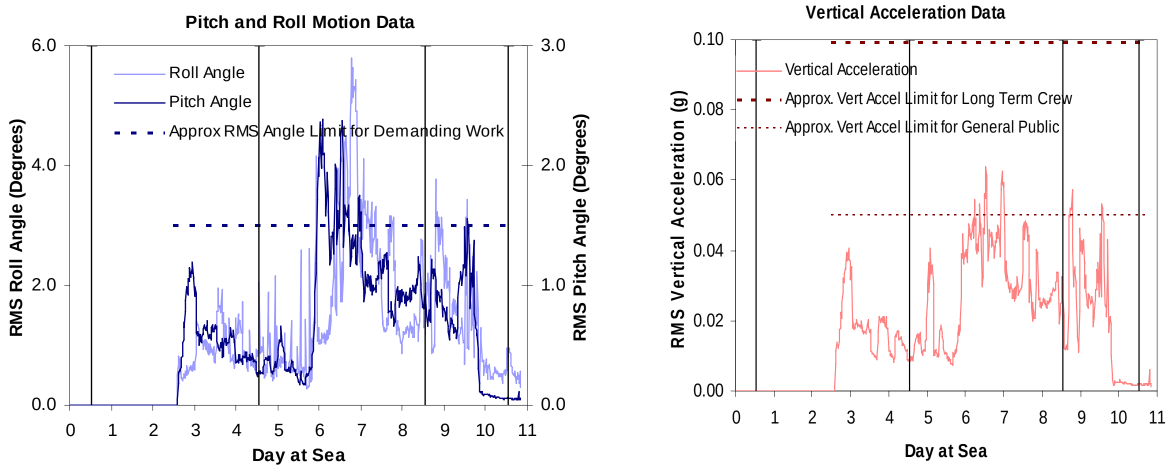


Figure 6: Plots of horizontal and vertical RMS roll and pitch and vertical acceleration over the duration of the trial. The vertical lines indicate when the test sessions were performed.

3.3.1 Differences between Experimental Sessions

A Friedman test of probability of equal categories was performed at each character height to assess whether there was any effect of session on identification error or certainty performance. The results shown in Table 10 show that the experimental session only had a significant effect on errors for a character height of 16 min. Thus the experimental session did not appear to have a reliable effect on error or certainty. It is not clear why this was the case. It may have been because the ship's motion was not consistently above heuristic thresholds necessary to induce adverse effects, but it should also be noted that a sample size of 12 may not provide enough power to yield statistically significant results. Given these results, the data from Sessions 2 and 3 were combined into an "at-sea" condition for further analysis.

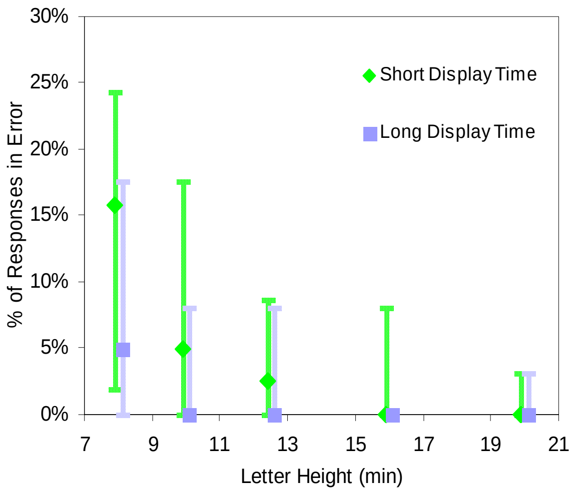
*Table 10: Results of Friedman tests to examine the effect of experimental session on identification error or certainty. * indicates p < .05.*

Character Height (min)	df	Errors		Certainty	
		Chi-Square	p	Chi-Square	p
8	3	0.8	.856	4.4	.219
10	3	5.0	.172	0.3	.952
12.5	3	3.2	.357	4.2	.243
16	3	9.0	.029 *	4.3	.228
20	3	1.0	.081	1.9	.585

3.3.2 The Effect of Letter Size and Display Time

Having determined that combining data from Sessions 2 and 3 would best generalise the target population of naval combat system operators under at-sea operational conditions, the effect of letter height on accuracy, certainty and response time for data from these sessions were examined. As discussed in the introduction, convincing evidence exists that the visual

information necessary to reach an identification decision is collected within the first 100 ms of viewing. However, fixations generally have an average duration of approximately 200 ms, and it is thought that it is possible for information to be processed throughout the fixation period. Thus it may be possible to maintain reading speeds while processing information at the fixation point for longer than 100 ms. To explore this, the effect of text size on identification performance of white letters was examined for display time conditions of 106 ms and 173 ms.



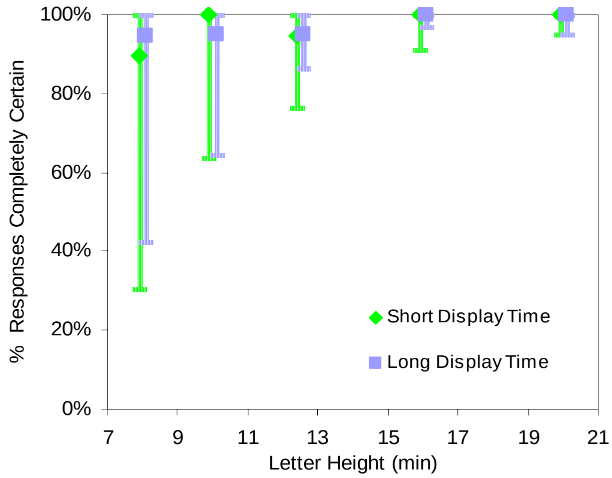


Figure 7: Plots of median identification error and certainty for white letters at each stimulus height for a 106 ms and a 173 ms display time during combined at-sea test sessions. Error bars represent the 75th percentile range.

*Table 11: Results of Wilcoxon signed ranks tests to determine the character height at which identification error and certainty for white letters significantly differed from the maximum character height for 106 ms and 173 ms display times using the combined at-sea test sessions. * indicates p < .05.*

Character Height (min)	df	Display Time 106 ms Z	p		Display Time 173 ms Z	p	
Errors							
8.0	1	-2.9	.005	**	-2.3	.024	*
10.0	1	-2.4	.017	*	-1.5	.131	
12.5	1	-2.2	.026	*	-1.1	.257	
16.0	1	-1.2	.223		-0.6	.564	
Certainty							
8.0	1	-2.5	.011	*	-2.3	.021	*
10.0	1	-1.8	.080		-1.8	.068	
12.5	1	-2.4	.018	*	-1.9	.056	
16.0	1	-0.1	.891		-1.6	.102	

As seen in Table 11, the different display times led to different character heights at which identification error and certainty became significantly different from that of the maximum character height. For the 106 ms display time condition, letter heights of 12.5 min and below had significantly more errors when compared to the maximum character height of 20 min.

Certainty was also significantly lower than at the maximum height for letter heights of 8 min and 12.5 min. This result would suggest that white letters should have a minimum height of 16 min to optimise visual identification performance at sea. For the 173 ms display time condition, only letters with a height of 8 min had error and certainty rates that were significantly different from the maximum letter height. However an inspection of Figure 7 indicates that even with this extended display time a trend towards degraded identification performance was evident for letter heights lower than 16 min.

The minimum letter height results vary between Experiments 1 and 2, and this could be due to differences in the nature of the samples or the testing environment. Given that both the participants and environmental conditions of Experiment 2 are more closely aligned with the operational conditions under which the combat management system will be used, it could be argued that the results of Experiment 2 should take precedence. However, in addition to the different participant samples and testing environments, a different display screen was also used in each study. Experiment 1 used a LCD similar to that proposed for use in a combat management system console but Experiment 2 used a laptop with a display which was smaller and had lower resolution. The different screens may have contributed to the differences between Experiment 1 and Experiment 2; to address this concern a third experiment was conducted in which a subset of Experiment 1 participants was retested using the apparatus and procedure of Experiment 2.

4. Experiment 3 –Comparison of Screens

4.1 Introduction

Experiment 2 was conducted with a different sample of participants who performed the tests in a different environment and on a different screen than used in Experiment 1. Both the sample and environment of Experiment 2 are closer to the actual population and environment that the CMS displays will be used in and thus the results of Experiment 2 potentially have greater external validity than those of Experiment 1. The reverse was true for the display screens, with Experiment 1 using a display that is similar to that proposed for use in a CMS and Experiment 2 using a laptop with lower resolution. Although the stimulus size and viewing distance in Experiment 2 were adjusted to create an equivalent pixel density to that of Experiment 1, the possibility exists that the different displays were causing the differences in minimum acceptable character heights seen between Experiment 1 and 2. To address these concerns, a final Experiment was performed in which the participants of Experiment 1 who experienced the ambient light and screen-background luminance conditions used in Experiment 2 and were still available were re-tested using the apparatus and procedure of Experiment 2. If a significant difference was found between the two Experiments, it would suggest that the screen may have influenced the results of Experiment 2.

4.2 Method

4.2.1 Participants

Nine of the participants who were tested under dark ambient lighting in Experiment 1 were available to participate in Experiment 3. Five of the participants were male and the average age of the participants was 34.1 years (SD = 6.0).

4.2.2 Apparatus

The same equipment as in Experiment 2 was used.

4.2.3 Stimulus

The stimuli of Experiment 2 were used.

4.2.4 Procedure

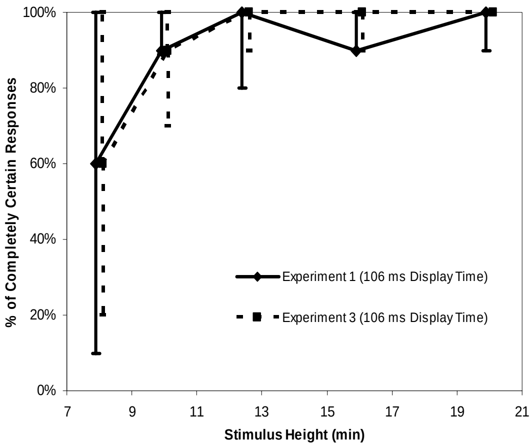
The same procedure as Experiment 2 was used, with the exception that only one experimental session was conducted for each participant. All participants were tested under dark ambient lighting (1.5 lux measured above the display).

4.3 Results and Discussion

The mean percentage of error and "Completely Certain" responses for each letter height for the participants common to both Experiment 1 and 3 is shown in Table 12, and plots of the certainty results are shown in Figure 8. Wilcoxon signed ranks tests were performed to determine the character height. At which the percentage of "completely certain" responses became reliably different from the percentage of "completely certain" responses observed at a character height of 20 min. The results of these tests are shown in Table 13.

Table 12: Median percentage of error and "Completely Certain" responses for white letters at each display time for Experiment 1 (DSTO sample, Apple LCD monitor) and Experiment 3 (DSTO sample, Sony VAIO LCD monitor). The inter-quartile range is in parentheses.

	Character Height (min)	106 ms Display Time				173 ms Display Time			
		Experiment 1		Experiment 3		Experiment 1		Experiment 3	
Errors	8.0	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(10.0%)
	10.0	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)
	12.5	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)
	16.0	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)
	20.0	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)
Certainty	8.0	60.0%	(40.0%)	60.0%	(50.0%)	80.0%	(50.0%)	70.0%	(50.0%)
	10.0	90.0%	(10.0%)	90.0%	(20.0%)	100.0%	(20.0%)	90.0%	(10.0%)
	12.5	100.0%	(0.0%)	100.0%	(10.0%)	100.0%	(0.0%)	100.0%	(0.0%)
	16.0	90.0%	(10.0%)	100.0%	(0.0%)	100.0%	(0.0%)	100.0%	(0.0%)
	20.0	100.0%	(0.0%)	100.0%	(0.0%)	100.0%	(0.0%)	100.0%	(0.0%)



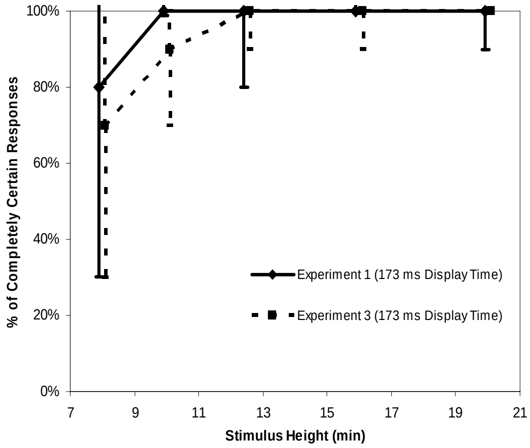


Figure 8: Plots of median identification certainty for white letters at each stimulus height, using the nine participants common to Experiments 1 and 3.The left plot is for a 106 ms display time, and the right plot is for a 173 ms display time. Error bars represent the 75th percentile range.

Table 13: Results of Wilcoxon signed ranks tests to determine the character height at which identification certainty for white letters significantly differed from a character height of 20 min for the common participants of Experiments 1 and 3. The table shows both the 106 ms and 173 ms display time conditions.

Character Height (min)	df	106 ms Display Time				173 ms Display Time			
		Experiment 1		Experiment 3		Experiment 1		Experiment 3	
		Z	p	Z	p	Z	p	Z	p
8.0	1	-2.37	0.018 *	-2.38	0.018 *	-2.54	0.011 *	-2.37	0.018 *
10.0	1	-2.06	0.039 *	-2.03	0.042 *	-1.63	0.102	-2.12	0.034 *
12.5	1	-0.82	0.414	-1.00	0.317	-1.00	0.317	-1.00	0.317
16.0	1	-1.67	0.096	-1.00	0.317	-1.00	0.317	0.00	1.000

Table 13 shows that for the participants common to both Experiment 3 and Experiment 1, there was a significant reduction in identification certainly for character heights less then 12.5 min in 106 ms display time condition. In other words, for both display screens, identification certainty was affected at the same character height. For the 173 ms display time condition, a reduction in certainty was seen for character heights below 10 min for the sub-set of Experiment 1 participants common to Experiment 3, and for character heights below 12.5 min in Experiment 3. This could be interpreted as indicating that the screen used in Experiment 3 led to lower identification certainty. However, as it is inconsistent with the results of the 106 ms display time condition, which would appear to be a more stringent test of the effect of different screens, and also with the results of Experiment 1 when including all participants, it appears more likely to be a Type II error.

To support this interpretation, repeated-measures Wilcoxon signed ranks tests were also used to examine whether accuracy or certainty varied between Experiment 1 and Experiment 3 at character heights of 8 min and 10 min. No significant differences were found at either character height in either the 106 ms display time condition, where $Z(8) = -0.11$, $p = .916$ for

8 min characters and $Z(8) = -0.72$, $p = .458$ for 10 min characters, or in the 173 ms display time condition, where $Z(8) = -.63$, $p = .526$ for 8 min characters and $Z(8) = 0.00$, $p = 1.000$ for 10 min characters.

While these results suggest that the different display screens did not give rise to different error or certainty results, it should be noted that it cannot be considered conclusive. The sample size was small and caution is always necessary in drawing conclusions from null results. In addition, all participants undertook Experiment 3 after Experiment 1, and it may have been that the effect of display screen was masked by an order effect. However, there was no difference in accuracy or certainty levels over the period of each trial block of Experiment 1, which suggests that, perhaps as expected for a simple perceptual task with over-learned stimuli, there was not a significant effect of practice or time-on-task.

Thus while it is difficult to definitively exclude the influence of order effects when comparing the results of Experiment 1 and 3, practice, as measured by time-on-task, did not appear to affect the results of Experiment 1. Hence, it appears unlikely that they would mask a decrease in performance due to the display screen when comparing Experiments 1 and 3. Thus it appears that the identification accuracy and certainty results in Experiments 1 and 2 were insensitive to the fact that different display screens were used.

5. General Discussion

Experiment 1 aimed to test the minimum text and symbol size necessary to maintain fast, accurate and confident identification of text and symbols. It presented letters, numbers and symbols at sizes ranging from 20 min to 8 min high for periods of 106 ms and 173 ms and measured the size at which identification accuracy and certainty began to decline. The findings suggest that white and coloured letters and numbers must have a height of 10 min or greater to maintain non-significant error rates, and have a height of at least 12.5 min to maintain high identification certainty. White and coloured symbols must have a height of 12.5 min or greater to maintain both accuracy and certainty of identification. However, these results were obtained in the absence of the potentially detrimental effects of ship motion effects that are likely to occur during naval operations.

To address this concern, Experiment 2 conducted measurements four times during a 12-day sea trial, which was conducted off the coast of Halifax, Nova Scotia, in a period where heavy seas were expected. The study aimed to identify whether any change in the identification performance was evident over the course of the sea trial, and to identify the minimum height of white letters needed to maintain optimum identification performance under conditions similar to those experienced during naval operations, i.e., high sea states and possibly sea-sick operators.

Based on combined data from the at-sea measurements of Experiment 2, a character height of 16 min was necessary to maintain identification accuracy and certainty for white letters in the 106 ms display time condition. This would suggest that white letters should ideally have a height of 16 min or greater. However, accuracy and certainty improved if a viewing time of

173 ms was allowed, and, under this condition, the white letter height necessary to maintain identification accuracy and certainty reduced to 10 min.

Experiment 1 tested white and coloured letters, numbers and symbols while Experiment 2 only tested white letters. Thus a direct comparison of results can only be done for this stimulus category. For white letters, the results of Experiments 1 and 2 differed in the relationship of the certainty and accuracy results, the effect of display time and the minimum character height necessary to maintain identification performance. In Experiment 1, identification certainty was affected at a larger letter height than identification error, whereas in Experiment 2, identification error and certainty were affected at the same letter height. The differences in the certainty results can possibly be explained by the nature of the two samples. Experiment 2 participants were defence force personnel who, by a combination of disposition and training, may be confident in their decisions and opinions. In contrast, Experiment 1 participants were DSTO scientists who, it might be argued, may tend to be more tentative in their decision making. This explanation is of course rather speculative but, whatever the reason for the group differences, it would seem prudent to base minimum character height recommendations on the measure that is most sensitive for each group. Thus Experiment 1 would suggest a minimum white letter height of 12.5 min and Experiment 2 would suggest a minimum white letter of 16 min for a display period of 106 ms and of 10 min for a display period of 173 ms.

It would also seem prudent to base recommendations on the results of the 106 ms display time condition, as this would ensure optimum identification performance. Thus the results of Experiment 1 would suggest that the minimum white letter height should be 12.5 min and the results of Experiment 2 would suggest that the minimum white letter height should be 16 min. Given that the results of Experiment 2 were likely to incorporate any detrimental effects of the at-sea environment and were based on a participant sample that closely matched the expected target population, it can be recommended that 16 min or arc is the minimum height of white letters displayed on naval combat management systems. Given that, in Experiment 1, white and coloured letters, numbers and symbols were all found to need a minimum character height of 12.5 min to maintain optimal identification performance in an on-land environment, it seems reasonable to conclude that these characters should have also have a minimum height of 16 min when displayed in naval combat management systems.

While 16 min may be required for optimal identification performance, an average fixation lasts approximately 200 ms. Therefore, if characters can be identified within this period, there will be no practical effect on reading speed. For a viewing time of 173 ms (which is similar to the length of an average fixation), the results of Experiment 2 suggest that white letters with a height of 10 min could be accurately and confidently identified. This raises the possibility that, while not allowing for optimal identification performance, reducing the size of white letters on a naval combat management system display to a height of 10 min may not have a substantial effect on reading speed. However, the sample size of Experiment 2 was small, which may limit its statistical power to detect changes in identification performance. This possibility is supported by an inspection of the data, which shows the existence of a trend for accuracy and confidence to reduce for letter heights below 16 min, even if a significant result was not obtained until letter heights were below 10 min. Thus while increasing the viewing time from 106 ms to 173 ms may mean that the minimum letter height can be reduced from

16 min, it would seem imprudent to suggest that 10 min is acceptable. In Experiment 1, the highest error rates were seen for white and coloured symbols, and there was a steep increase in identification errors for symbol height below this. Given this, it would seem reasonable to suggest that characters displayed on a naval combat management system must have a minimum height of 12.5 min of arc in order to support rapid and accurate identification.

6. Conclusions

For an LCD with luminance and contrast settings appropriate for the prevailing ambient light levels, the following recommendations can be made about character size and colour:

- White and coloured numbers, letters and combat symbols *must* be displayed at a minimum character height of 12.5 min in order to support rapid and accurate identification, and *should* be displayed at a minimum character height of 16 min to enable optimum identification performance in an at-sea environment.
- The use of red is not recommended unless the colour is being used to convey information. In this case a blended red may be preferable to pure red for text and symbols.

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19. ABSTRACT

This study aimed to identify the minimum font size that supports fast and accurate identification of text and symbols displayed on an LCD under ambient lighting conditions similar to those in naval ships' operations rooms. A series of letters, numbers and combat symbols were displayed on an LCD for either 106 ms or 173 ms. Participants were asked to identify each stimulus and the certainty of their decision. Letters and numbers were presented in white, red, green and cyan, and symbols were either white or colour-coded. The stimulus heights subtended angles of between 8 minutes and 20 minutes. The study identified the minimum height at which accuracy and certainty were not significantly reduced. Two experiments were performed: one on a land-based sample, and one using Canadian Defence Force personnel during a sea trial in an attempt to identify the potential affects of ships motion and fatigue. Colour significantly improved the identification accuracy and certainty of symbols. Red numbers and letters were identified with significantly lower confidence than white, green or cyan. Some performance degradation was observed during the sea trial, and it is suggested that text and symbols ideally have a height of 16 min or greater, but that a height of 12.5 min or greater is acceptable. A height of less than 12.5 min must not be used for text or symbols that need to be rapidly identified.

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